

Optimization of Anti-Reflection Layers for Deep UV Lithography

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Abstract

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Increasing swing and notching effects due to the higher reflectivity of silicon with decreasing exposure wavelength are a major problem in Deep UV lithography. Top and/or Bottom Anti Reflective Layers (ARL) are necessary for sub-half micron lithography.

In this article a simple method is described how optimum values of the refractive index and the thickness of Bottom ARL's can be determined.

Two classes of Bottom ARL's exist:

I) materials with low intrinsic reflectivity in resist; the thickness of these ARL's is non-critical above a minimum value.

II) Bottom ARL's based on the combined effect of absorbance and interference, so that ARL thickness control over topography is critical.

The advantages and disadvantages of both ARL types are given. On poly-Si the optimum ARL is a combination of the two types. A quantitative comparison of the usefulness of various materials as ARL on (poly)silicon, oxide and aluminum is made. Materials considered are: spin-on organic ARC, TiW, TiN, and plasma-enhanced CVD deposited amorphous layers such as hydrogenated silicon (a-Si:H), carbon (a-C:H), silicon carbide a-SiC_x, oxynitride a-SiN_xO_y, and nitride a-Si_{3+x}N₄.

1. INTRODUCTION

As the linewidths in IC manufacturing decrease, the use of shorter wavelength light in the projection tools is advantageous. For 0.35 μm and 0.25 μm lithography 365 nm (i-line) and 248 and 254 nm (Deep UV) are the wavelengths to be used. With decreasing wavelength the reflectivity of silicon increases. Consequently, notching and swing effects increase. Notching is the effect that light reflected from the topographic substrate becomes concentrated at certain positions, so that local linewidth narrowing or broadening occurs. Swing is the effect that the linewidth varies due to thin film interference effects caused by resist thickness variation or by thickness variation of transparent layers - such as oxide or nitride - underneath the resist layer.

There are several ways to reduce these problems. A dyed resist is the simplest solution, but dyeing often goes accompanied by a loss in resolution and latitudes. A Top Anti Reflection Coating (Top-ARC) can reduce the swing effect, but does not reduce notching problems. A Bottom Anti Reflection Layer (ARL) can eliminate both swing and notching problems, but is also the most elaborate solution.

The outline of this paper is as follows:

In section 2 it will be discussed how the optical parameters of substrate and resist, together with other resist parameters, influence the swing effect. The optimum values of the real and imaginary part of the refractive index and the thickness of a Bottom ARL on poly-Si are calculated in section 3. Various possible ARL materials will be discussed. In section 4 different materials as ARL on Aluminum are compared. The extra constraints on an ARL, when used on transparent layers are discussed in section 5, while in section 6 a comparison is made of using an ARL on top of or underneath an oxide layer.

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The problems of applying, etching and removing the ARL's are not discussed in this article, although they may be decisive for the choice for a certain ARL.

2. IMPORTANT PARAMETERS FOR SWING EFFECTS

Reflective notching is the result of imaging light reflected from the substrate back in the resist. Swing, however, is due to thin film interference effects in the resist film. So, for swing effects both the reflection from the substrate/resist interface and from the resist/air interface are of importance. Brunner [1] derived a simple expression for swing:

$$S_{En} = 4\sqrt{R_{top} \cdot R_{bottom}} e^{-\alpha \cdot D_{Resist}} \quad (\text{Eq. 1})$$

where swing S_{En} is the variation of the amount of energy absorbed in the resist film, R_{top} is the reflectivity of the resist/air interface, R_{bottom} the reflectivity of the resist/substrate interface, α the resist absorption coefficient and D_{Resist} the resist thickness.

Swing problems increase from g-line to i-line to Deep UV, since the reflectivity of silicon in resist (R_{bottom}) increases from 24 % for 436 nm light, to 41 % for 365 nm and to 55 % for 248 nm. Since typical values for the refractive index of resist are 1.65, 1.67 and 1.80 for the three wavelengths, respectively, also R_{top} increases with 35 % from g-line to Deep UV. Furthermore, the resist thickness difference between maximum and minimum incoupling ($\lambda/(4 \cdot n_{Resist})$) decreases from 66 nm for g-line to 34 nm for Deep UV.

From Eq. 1 it can be seen that in order to reduce the swing one can either:

- 1) increase the absorbance of the resist, which has the disadvantage of loss of resolution, and of focus and exposure latitude [2].
- 2) decrease the resist/air reflectivity R_{top} by using a Top-ARC. Tanaka et al. [3] showed that a good matching of the refractive index of the Top-ARC to $\sqrt{n_{Resist}}$ can reduce the swing to zero, when the thickness of the TopARC is $\lambda/(4 \cdot n_{Top-ARC})$. Notching is not reduced by using a Top-ARC.
- 3) decrease the resist/substrate reflectivity R_{bottom} by using a Bottom ARL [4-6], which also has the advantage that notching is suppressed. Since a good Bottom ARL can solve all problems, the rest of this paper will deal with Bottom ARL's only.

The effect of the absorbed energy swing on the Critical Dimension (CD) swing S_{CD} can be estimated by the Exposure Latitude (EL). With a higher exposure latitude the same amount of variation in absorbed energy (Eq. 1) will lead to less variation in linewidth. The EL is commonly defined as the amount (or percentage) of exposure energy variation that gives a linewidth variation of ± 10 %. Assuming a linear relation between linewidth and exposure energy, the CD swing S_{CD} is

$$S_{CD} = S_{En} \cdot 20/EL \quad (\text{Eq. 2})$$

In Eq. 2 all values are in % and the 20 comes from the ± 10 % CD variation in the definition of exposure latitude. Increasing the exposure latitude is thus also an effective way to reduce CD swing.

As an example, Deep UV patterning of Shipley acid-hardening resist XP89131 is used to check the validity of the above calculations. With an ASM-L PAS5000/70 (NA=0.42) KrF stepper the CD swing is 123 nm for 0.4 μm lines/spaces [7] (see Fig. 1). The measured exposure latitude is 22 %. The calculated energy swing

from Eq. 1 is $S_{En}=46\%$ ($R_{bottom}=52\%$, $R_{top}=8.2\%$, $n_{resist}=1.80$, $\alpha=0.56\ \mu\text{m}^{-1}$) at a thickness of $1\ \mu\text{m}$. According to Eq. (2) a CD swing of 40 %, or 140 nm is expected. This value is in reasonable accordance with the measured CD swing of 123 nm.

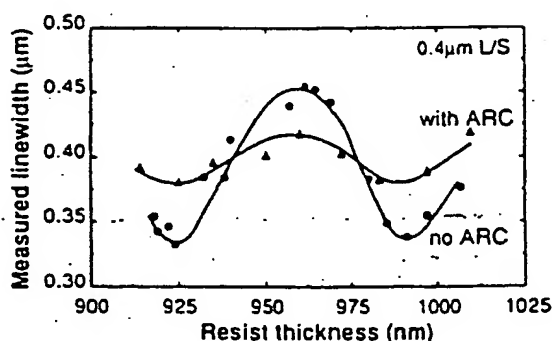


Figure 1 The linewidth swing of Shipley XP89131 (a) on silicon and (b) on 175 nm Brewer ARC11.

If a reduction of the CD variation in best focus due only to swing to $\pm 5\%$ of the linewidth is necessary, the swing for XP89131 on Si has to be reduced from 123 nm to 40 nm, i.e. by a factor 3. According to Eq. 1 R_{bottom} should thus be decreased by a factor 9, from 52 % to 6%. As an example, when $R_{bottom}=5\%$, using 175 nm Brewer ARC11 on Si, the measured swing is reduced to 37 nm or 9 % [7](see Fig. 1), which corresponds well with the calculation.

One can argue about the precise value of substrate reflectivity required, but this example shows that, because swing scales with $\sqrt{R_{bottom}}$, the reflectivity has to be brought down to quite low values. The above derived R_{bottom} value of 6 % will be used in the rest of this article. For such low reflectivity values notching definitely is suppressed.

3. BOTTOM ARL: OPTIMIZATION OF REFRACTIVE INDEX AND THICKNESS

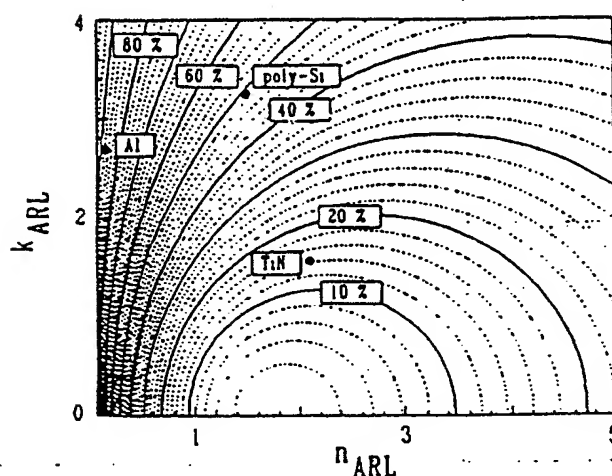


Figure 2 Contour plot of the reflectivity in resist (in %) as a function of the n and k values of a thick Bottom ARL.

In the previous section it was shown that when a Bottom ARL is used, it is desirable to bring the resist/substrate reflectivity R_{bottom} down to values in the order of 6 %. How the reflectivity in resist depends on the real part (n) and imaginary part (k) of the refractive index of the substrate material is shown in Fig. 2. Note, that this is the reflectivity at the interface between two semi-infinite media. For the Shipley XP89131 resist $n=1.80$ and $k=0.011$. Al ($R=87\%$), poly-Si ($R=49\%$) and TiN ($R=14\%$) are indicated in the figure. Zero reflectivity is found where the refractive index of the substrate material is identical to that of the resist. Reflectivity values below 10 % are found when n_{ARL} lies between 1.5 and 3, while k_{ARL} is smaller than 1. The question to be answered is what the optimum k -value of an ARL material is, because on one hand a material with a small k value can give very low reflectivity (see Fig. 2), but on the other hand it is transparent, so that interference effects due to the reflectivity of the underlying layer becomes pronounced. A higher k -value makes the material more opaque, but the reflectivity at the substrate-resist interface increases. Note that the minimum ARL thickness D_{ARL} necessary to make the material opaque is inversely proportional to k_{ARL} , since the transmission through a film is proportional to $e^{-\alpha D_{ARL}}$, where $\alpha = 4\pi k_{ARL} / \lambda$. The transmission through an ARL is less than 5 % when $k_{ARL} D_{ARL} \geq 60$ nm.

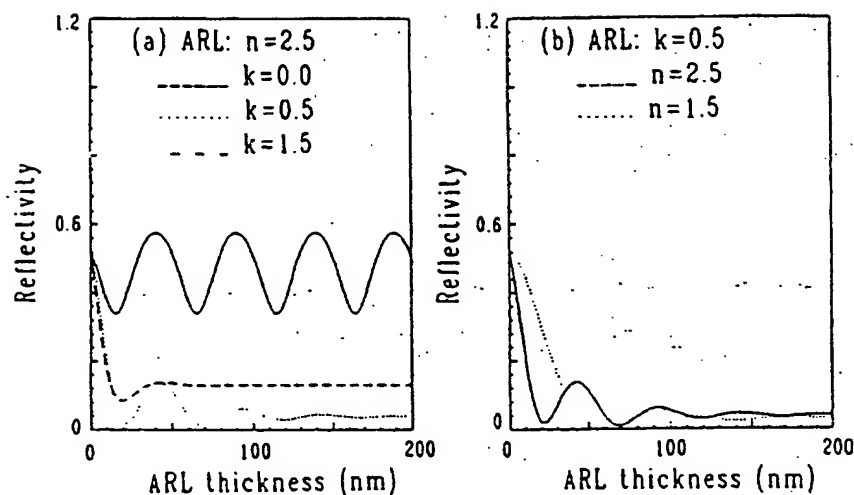


Figure 3 The reflectivity in resist of ARL on silicon as a function of the ARL thickness. (a) $n_{\text{ARL}}=1.3$ (b) $k_{\text{ARL}}=0.5$.

In Fig. 3a the reflection of an ARL on silicon as a function of the ARL thickness is plotted for different values of k_{ARL} , while $n_{\text{ARL}}=2.5$. $k_{\text{ARL}}=0$ means that the ARL is completely transparent. The reflectivity in resist R_{bottom} - now of the Si substrate plus ARL - is periodic and shows a first minimum at a thickness of about $\lambda/(4 \cdot n_{\text{ARL}})$. This is an example of a completely transparent ARL, whose anti-reflective working is only based on interference, and not on a low intrinsic reflectivity at the resist ARL interface, as calculated in Fig. 2. Top-ARC's are also based on this interference principle. The extremum at $\lambda/(4 \cdot n_{\text{ARL}})$ thickness is a minimum, because $n_{\text{resist}} < n_{\text{ARL}} < n_{\text{Si}}$. Better matching of the n_{ARL} can reduce the minimum reflectivity value further, but the very small thickness latitude of purely interference based ARL's with low reflectivity makes them unsuited for use on topographic substrates.

When $k=0.5$ the anti-reflection behaviour is stronger and based on the combined effect of absorption and interference. Their relative importance is dependent on the ARL thickness. For layers thicker than 120 nm only minor variation of reflectivity with thickness is observed, which means that the layer is opaque for these thicknesses. On the other hand, the low first reflectivity minimum around 20 nm is mostly due to interference. With increasing ARL thickness the interference effect becomes more damped. For $k=1.5$ in Fig. 3a the interference effect becomes already damped at an even lower ARL thickness. From 40 nm on the reflectivity is constant. However, the intrinsic reflectivity value is higher than for $k=0.5$, in accordance with Fig. 2. Due to the strong interference damping, the first reflectivity minimum value for $k=1.5$ is not so low as for $k=0.5$.

How the reflectivity depends on the real part of the refractive index n is shown in Fig. 3b. For a constant value of k_{ARL} the ARL is (partly) transparent up to a thickness, only dependent on k and not on n . However, when n_{ARL} is decreased, less interference periods are found within that thickness range and the first interference minimum is found for thicker layers.

It is worthwhile to discern here between two types of ARL:

- Type-I: "Matched" ARL's with a low intrinsic reflectivity in resist, since the refractive index of the ARL is matched to that of the resist. The reflectivity in resist of such ARL's is given in Fig. 2. ARL thickness control is not critical, as long as the thickness is so large that the layer is opaque for the imaging light. This is achieved when $k_{\text{ARL}} \cdot D_{\text{ARL}} \geq 60 \text{ nm}$. Low reflectivity is obtained for k_{ARL} values less than 1 (see Fig. 2), which means that rather thick ARL layers are necessary.
- Type-II: "Interference" ARL's, based on the combined effect of interference and absorption. Although interference is the main cause for the low ARL reflectivity, the ARL absorption is essential in order to get enough thickness latitude. Zero-absorbance quarter-wavelength films are a special case of Type-II ARL's. Zero reflectivity is possible with Type-II interference ARL's for $k_{\text{ARL}} > 0$. The optimum ARL thickness is the first interference minimum, at about $D_{\text{ARL}} \approx \lambda / (4 \cdot n_{\text{ARL}})$, and thickness control is very important. Note that it is possible to use the same material as a Type-I ARL for thick layers and as a Type-II ARL for a thin layer.

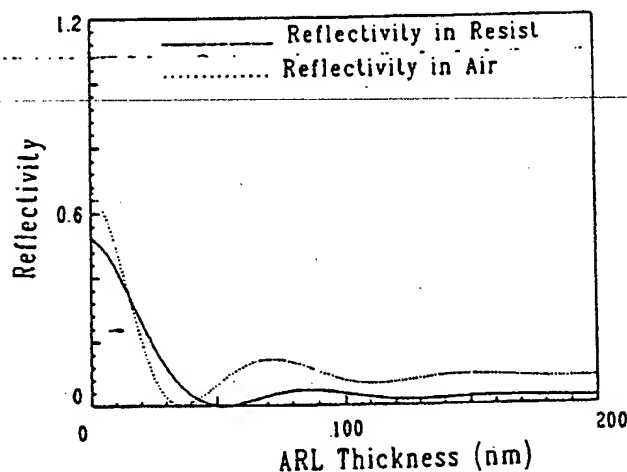


Figure 4 Reflectivity of Brewer ARC11 in air and in resist.

For optimization of the ARL absorption and thickness it is important to discern between the reflectivity in resist and in air. When n_{ARL} is close to the value of n_{Resist} and n_{Air} the reflectivities in resist and in air become significantly different (see Fig. 4). The reflectivity of a thick ARL in air is higher than in resist, when $(n_{\text{ARL}} - n_{\text{Air}})$ is larger than $(n_{\text{ARL}} - n_{\text{Resist}})$, and the ARL thickness of minimum reflectivity in resist is larger than for the reflectivity in air.

What are the optimum combinations of n_{ARL} , k_{ARL} and D_{ARL} ? To answer this question contours of constant reflectivity in resist of poly-Si with ARL as a function of D_{ARL} and k_{ARL} are given in Fig. 5a. n_{ARL} was held constant at 2.5. A horizontal cross-section at $k=0.5$ through the contour plot is the second curve in Fig. 3a. Reflectivity values of 6 % or less are found in two regions as indicated in the figure. The concomitant

combinations of k_{ARL} and D_{ARL} are given in Table 1. Around 20 nm ARL thickness Type-II Interference ARL behaviour is found, and for layers thicker than 120 nm Type-I Matched ARL behaviour is observed. The two 6 % regions are separated by the first reflectivity maximum around 45 nm ARL thickness. For thicknesses from 55-120 nm also values below 6 % are found. This is a crossover region from interference ARL to matched ARL, a Combined Type-I+II ARL.

The reflectivity value of the first interference maximum can be reduced by increasing the k_{ARL} , i.e. going up in Fig. 5a. However, with higher k_{ARL} the reflectivity of the ARL/resist interface goes up due to the larger mismatch between k_{resist} and k_{ARL} (see the top-right part of Fig. 5a and also Fig. 2).

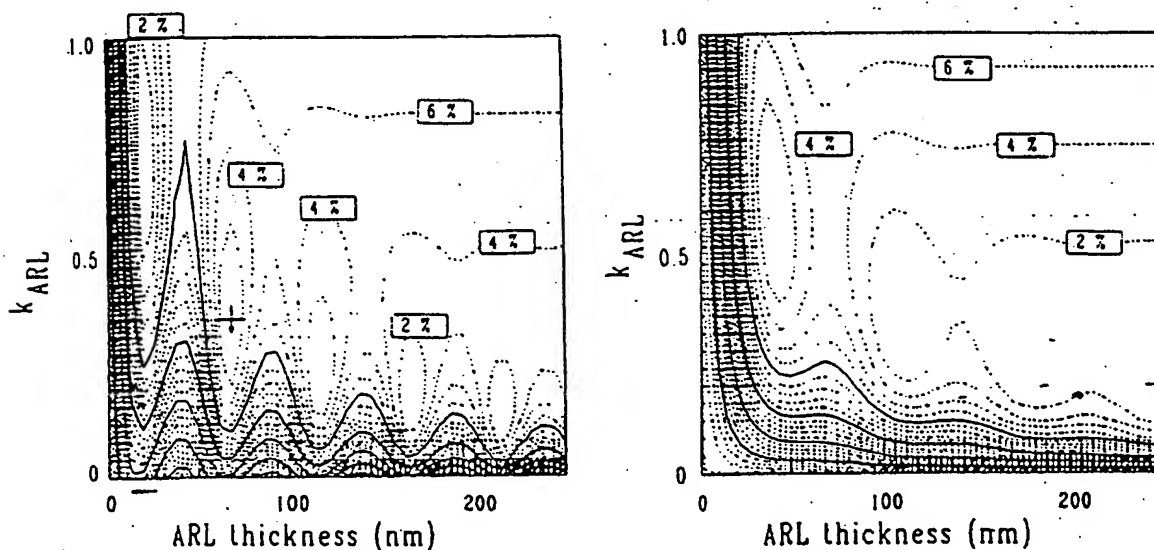


Figure 5 The reflectivity in resist of ARL on silicon as a function of the D_{ARL} and k_{ARL} . (a) $n_{\text{ARL}} = 2.5$ (b) $n_{\text{ARL}} = 1.8$.

A better way of decreasing the first interference maximum is reducing n_{ARL} . In Fig. 5b it is shown that for n_{ARL} is 1.8 the regions of $R_{\text{bottom}} < 6\%$ of the Interference and Matched ARL have merged. because the first interference maximum is less than 6 % for k_{ARL} between 0.35 and 0.85. An interference minimum is still observed at 40 nm ARL thickness, and matched ARL behaviour for thick layers. For the 2 % reflectivity level the two ARL types are still separated by the first interference maximum, but again, the interference behaviour is much less pronounced than in the $n_{\text{ARL}} = 2.5$ situation, where five 2 %-regions exist.

n_{ARL}	Interference (I) ARL		Combined (I+II) ARL
	$D_{\text{ARL}}(\text{nm})$	ARL thickness latitude	$D_{\text{ARL}}(\text{nm})$
2.5	22	$\pm 27 \%$	> 55
2.1	34	$\pm 35 \%$	> 62
1.8	43		> 29
1.5	62		> 41
1.2	80	$\pm 25 \%$	-

Table-1. Optimum thickness and thickness latitudes for ARL on poly-Si with $k_{\text{ARL}}=0.5$

In Table 1 data are collected where R_{bottom} values below 6 % are found, when $k_{\text{ARL}}=0.5$. For $n=2.5$ (Fig. 5a) the first interference minimum is found at 22 nm, and the thickness has to be controlled with $\pm 27 \%$. For $D_{\text{ARL}} > 55$ nm R_{bottom} is also smaller than 6 %. Pure Matched ARL behaviour is found for $D_{\text{ARL}} > 120$ nm. Between 55 and 120 nm the ARL is of the Combined interference plus matched type. For $n_{\text{ARL}}=1.8$ the first interference minimum is found for $D_{\text{ARL}}=43$ nm. However, since the first interference maximum has a value below 6 % the region of the Type-I and the Type-I+II ARL merge, and for all ARL thicknesses above 29 nm $R_{\text{bottom}} < 6 \%$. When $n_{\text{ARL}}=1.5$ the situation is similar, but the minimum D_{ARL} necessary is now larger. For $n_{\text{ARL}}=1.2$ values below 6 % for R_{bottom} are only found at the first interference minimum. For thicker layers R_{bottom} is larger than 6 % due to the increased mismatch between n_{ARL} and n_{resist} .

Overall, when n_{ARL} decreases the optimum thickness of a Type-II ARL increases, while the thickness latitude has a maximum at $n_{\text{ARL}}=1.7$, which is also the value where both types of ARL merge. Thus the optimum parameters for an ARL on poly-Si are: $n_{\text{ARL}}=1.7$, $k_{\text{ARL}}=0.6$ (see Fig. 5b) and $D_{\text{ARL}} > 28$ nm. Materials with $1.3 < n_{\text{ARL}} < 2.6$, and $0.3 < k_{\text{ARL}} < 0.9$ are also usable as ARL. Contour plots as Fig. 5 can be used to determine which R_{bottom} values can be obtained and what the optimum ARL thickness and the thickness latitude are.

A list of materials that can be used as ARL for Deep UV lithography is given in Table 2. The spin-on organic Brewer ARC will always be used at thicknesses larger than 100 nm, due to its deposition method. The other materials are Plasma Enhanced CVD deposited inorganic amorphous (a) compounds. The optical parameters of amorphous materials strongly depend on the deposition conditions. Next to the ARL materials already suggested in the literature - PECVD (hydrogenated) amorphous carbon [8], carbides [9] and oxynitrides [10] - PECVD (hydrogenated) amorphous $\text{a-Si}_{3+x}\text{N}_4$ can be used as ARL. Due to the non-stoichiometry of $\text{a-Si}_{3+x}\text{N}_4$, it becomes absorbing at low wavelengths (see Fig. 6), as measured by spectroscopic ellipsometry [11].

ARL	n_{ARL}	k_{ARL}	
ARC11	1.45	0.35	Brewer Science
a-C:H	1.75	0.50	Suda et al.[8]
a-SiC _x	2.36	0.53	Ogawa et al.[9]
a-SiO _x N _y	2.10	0.5-1.0	Ogawa et al.[10]
a-Si _{3+x} N ₄	2.40	0.45	

Table 2. Possible ARL materials.

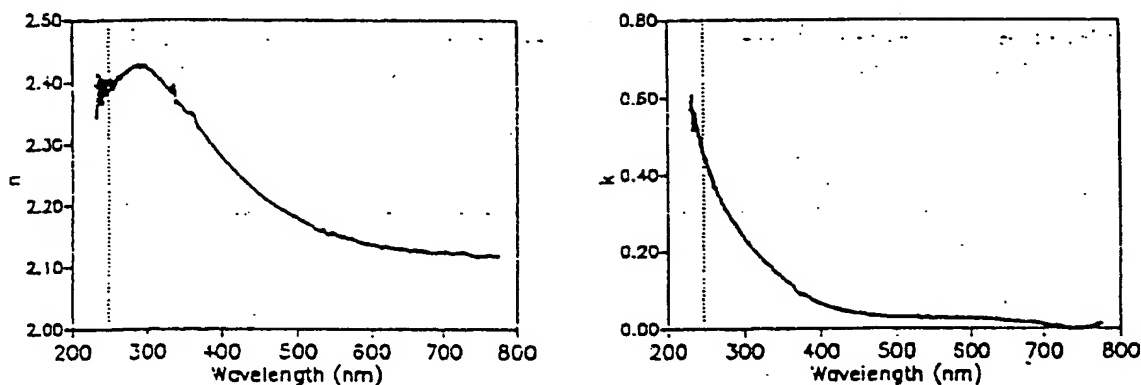


Figure 6 n and k of PECVD a-Si_{3+x}N₄.

The choice for a certain ARL depends on:

- R_{bottom} of the substrate (Si, silicide, Al, oxide,)
- the maximum R_{bottom} that is allowed, dependent on the minimum CD to be printed, and its exposure latitude
- the amount of topography which in combination with the step coverage of the ARL determines the minimum amount of ARL thickness latitude that is necessary
- the ARL deposition, plasma etching and stripping properties, which can be of decisive importance to make a material a usefull ARL

4. ARL MATERIALS FOR ALUMINUM

On Aluminum levels ARL's have already been around for a long time. The reflectivity of Aluminum in resist is around 90 % for g-line, i-line and Deep UV. In Fig. 7 the reflectivity in resist at 248 nm of 4 ARL candidate materials, that are also used for g- and i-line lithography, are plotted versus the ARL thickness. The minimum reflectivity necessary, depends on the linewidth to be printed and on the topography. It can be seen that TiN is also for Deep UV a suitable ARL material on metal levels. The above discussed PECVD

deposited amorphous inorganic materials and spin-on ARC can also be used as ARL on metal.

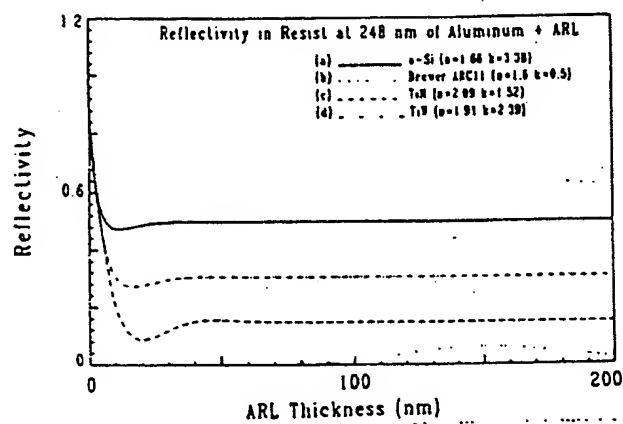


Figure 7 The reflectivity in resist of 4 ARL materials on aluminum.

5. BOTTOM ARL's FOR CONTACTS AND VIAS

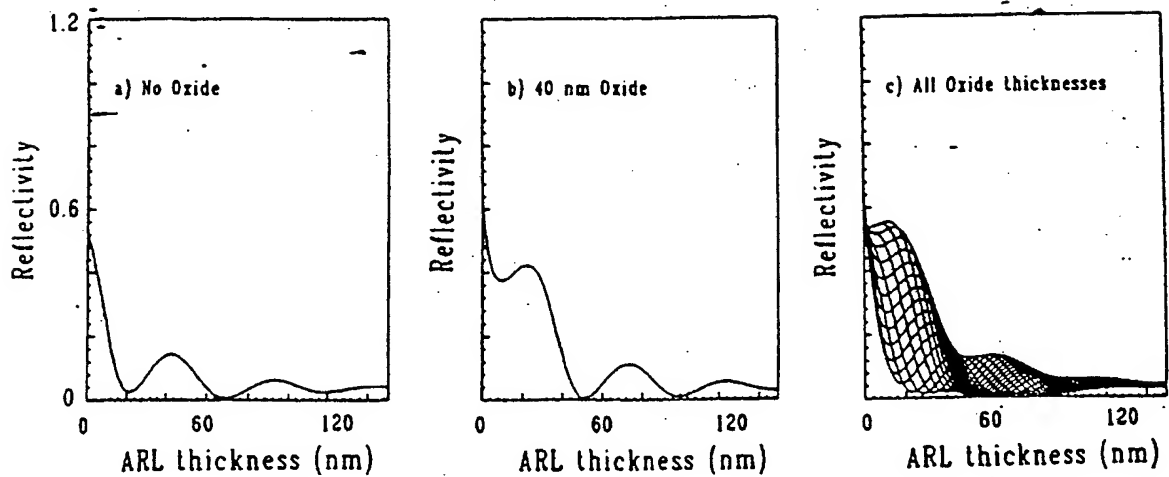


Figure 8 The reflectivity in resist of the stack silicon/oxide/a-Si_{3+x}N₄.
 (a) no oxide (b) 40 nm oxide (c) all oxide thicknesses.

Swing not only occurs when the resist thickness varies, but also when variations occur in the thickness of

transparent layers - planarizing oxide layers, for example - on top of reflective substrates, underneath the resist [12]. The question is, can these swing effects be handled by the same ARL's as used directly on reflective substrates. Fig. 8a shows the reflectivity in resist R_{bottom} of a silicon/ARL stack as a function of D_{ARL} , where $a\text{-Si}_{3-x}\text{N}_x$ was chosen as ARL. With 40 nm oxide between substrate and resist R_{bottom} behaves quite differently (see Fig. 8b). The reason for the difference is simple. On silicon an Interference ARL can be optimized on the combined effect of absorption and interference. Due to the transparency of such a thin ARL layer, the interference effect can work out disadvantageously for certain oxide thicknesses. In order to determine worst case behaviour, the reflectivity of the stack silicon/oxide/ARL is shown for oxide thicknesses from 0 to 85 nm in Fig. 8c. This thickness range is representative for all possible oxide thicknesses, since the reflectivity varies periodically with oxide thickness and 83 nm is a full swing period. From this plot it can be seen that 110 nm is the minimum ARL thickness to reduce R_{bottom} below 6 %, where 16-28 nm or more than 55 nm was enough on bare silicon.

A pure Type-II Interference ARL is thus unsuited on oxide. A Type-I Matched ARL is always good on oxide, since it is completely opaque. The minimum thickness necessary, for a Combined Type-I+II ARL, can be calculated as in Fig. 8c.

6. BOTTOM ARL ON TOP OF AND UNDERNEATH OXIDE LAYERS

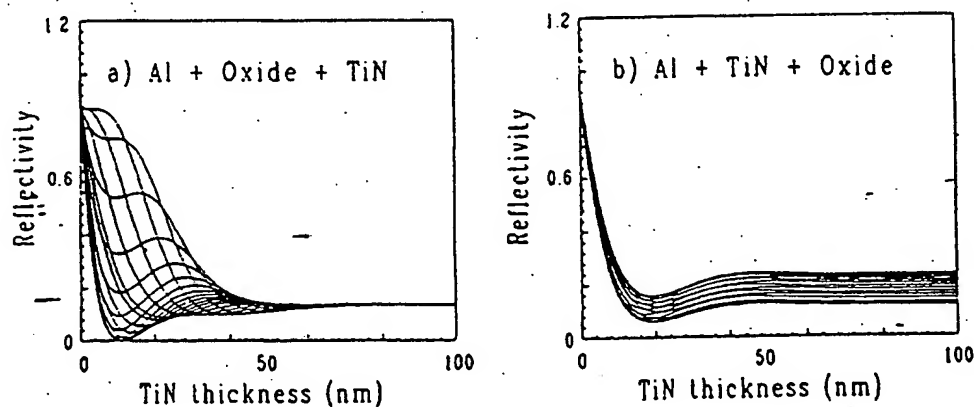


Figure 9 Reflectivity in Resist of the stacks (a) Al/TiN/Oxide and (b) Al/Oxide/TiN for all oxide thicknesses.

An ARL can not only be put on top of the oxide layer, but sometimes also below it. The difference in the reflectivity for these two possibilities is plotted in Fig. 9 for an Al substrate with TiN as ARL. In Fig. 9a R_{bottom} of an Aluminum/Oxide/TiN stack is plotted as a function of the TiN thickness for all possible oxide thicknesses. With TiN on top of oxide the reflectivity becomes the intrinsic reflectivity of TiN - 14 %, see Fig. 2 - for thicknesses above 50 nm, while for smaller thicknesses interference effects are still prominently present, as discussed in the previous section. However, for a TiN layer on Al with oxide on top of TiN R_{bottom} behaves quite differently see Fig. 9b). The lowest R_{bottom} values and the lowest variation in R_{bottom} are found at 18 nm TiN thickness. This is the thickness where the reflectivity in oxide of the Al/TiN stack is minimum, which is mainly due to interference. Thus, interference ARL's can not be used on top of oxide

layers. However, they can be used when deposited directly on the reflective layer, underneath the oxide. It depends on the maximum allowed R_{bottom} and ARL integration aspects, if an ARL under oxide can be used in a process.

7. CONCLUSIONS

In order to reduce swing and notching effects in Deep UV lithography Bottom Anti Reflection Layers are necessary. It has been shown that two types of Bottom ARL's exist:

- Type-I Matched ARL's, based on a low intrinsic reflectivity in resist, due to matching the refractive index of the ARL to that of the resist. Thickness control is not critical, because the ARL is so thick that it is opaque.

- Type-II Interference ARL's, based on the combined effect of interference and absorbance. The ARL thickness should be close to $\lambda/(4 \cdot n_{\text{ARL}})$, so that thickness control is critical.

For Deep UV lithography on poly-Si a Combined Type-I+II ARL - for which the n_{ARL} , k_{ARL} and D_{ARL} are chosen in such a way that the two ARL types merge - is the best choice. The optimum values of the refractive index are $n_{\text{ARL}}=1.7$ and $k_{\text{ARL}}=0.6$, while the ARL thickness should be larger than 30 nm. Also materials with $n_{\text{ARL}}=1.3-2.6$ and $k_{\text{ARL}}=0.3-0.9$ are usable as ARL, but they have a smaller thickness latitude. PECVD deposited amorphous $\text{Si}_{3+x}\text{N}_4$ is a good alternative to earlier reported materials. Furthermore, it has been shown that on oxide layers, as contact and via levels, Type-I ARL's based on interference are only suited when used under the oxide. ARL's on top of oxide should be opaque, of the matched Type-II.

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